Applied Ocean Research 63 (2017) 142–156

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Behavior of drag anchor in clay with linearly increasing shear strength under unidirectional and combined loading

Xiaoni Wu*, Yean Khow Chow, Chun Fai Leung

Center for Offshore Research and Engineering, National University of Singapore, 1 Engineering Drive 2, E1A-02-19, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 13 September 2016
Received in revised form
30 December 2016
Accepted 30 December 2016
Available online 19 January 2017

Keywords:
Finite element study
Soil non-homogeneity
Drag anchor
Capacity
Yield envelope

ABSTRACT

Drag anchor is a widely used economical anchor option for offshore floating structures. The anchor behavior under unidirectional loading and combined loading is important for anchor selection. The anchor behavior under combined loading, characterized by the yield envelope, can also be used for the prediction of anchor installation, which is still an issue in anchor design. However, most existing studies on anchor capacity are for plate anchors which focused only on the anchor pullout capacity in soil with uniform shear strength. The behavior of drag anchor under unidirectional and combined loading in soil with linearly increasing shear strength profile is seldom investigated. The current 2D finite element studies investigate the anchor behavior for a horizontal anchor fluke in clay with linearly increasing shear strength under unidirectional vertical, horizontal and rotational loadings first. Then based on the results of anchor unidirectional loading behavior, the yield envelopes for anchor under combined loading for both shallow and deep embedded flukes are studied. The effect of anchor embedment depth, soil non-homogeneity, soil overburden pressure and the soil/anchor interface breakaway conditions are studied to provide insight for drag anchor design.

1. Introduction

With the increase in applications of offshore floating structures in deep waters, different kinds of anchors are developed for the mooring system which connects the floating structures to the seabed by mooring lines and anchors. Anchoring options are available ranging from the traditional gravity anchor, anchor pile and drag embedment anchor (DEA) to the more recent vertical loaded anchor (VLA), suction caissons, suction embedded plate anchor (SEPLA), torpedo anchor and deep penetrating anchor. Although different anchoring options have their own strengths when examining the bearing performance or economics, drag anchors (DEA or VLA) are still the economical choice due to the simple installation, in which the anchor is dragged into the seabed soil until it reaches a depth which provides the designed capacity. The term drag anchor here is used to represent anchors with drag-in installation and the geometry of simplified traditional drag embedment anchor fluke without considering the shank will be used in the study.

Anchor bearing capacity and anchor installation behavior are two major issues of drag anchor design. The anchor performance under unidirectional loading and combined loading is important for anchor selection. The anchor behavior under combined loading characterized by the yield envelope can also be used for the prediction of anchor installation behavior, which is still an issue in anchor design. During anchor installation, the anchor fluke is subjected to combined vertical, horizontal and rotational loading. As the anchor is subjected to combined loading and the behavior during installation is different for different embedment depths and soil strength profiles, studies of anchor behavior under unidirectional loadings are necessary for understanding anchor behavior under combined loadings. Although drag anchors have been widely used, the capacity of anchor fluke has not been fully understood. Limited studies have been conducted to investigate the influence of linearly increasing soil shear strength on the anchor behavior, which is practical for offshore seabed. Therefore, the current analyses used the finite element method to investigate the anchor behavior for a horizontal anchor fluke in clay with linearly increasing shear strength under unidirectional and combined loadings.

Earlier studies on anchor capacity under unidirectional loading focused on plate anchor pullout capacity in uniform soil (such as [1–5]). Studies were also conducted to obtain the limiting capacity under three unidirectional loading conditions when deep localized failure occurs in uniform soil (such as [6,7]). However, a common soil undrained shear strength profile is increasing linearly with

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* Corresponding author.
E-mail addresses: wuxiaoni@u.nus.edu (X. Wu), chowyk@nus.edu.sg (Y.K. Chow), ceelcf@nus.edu.sg (C.F. Leung).

http://dx.doi.org/10.1016/j.apor.2016.12.011

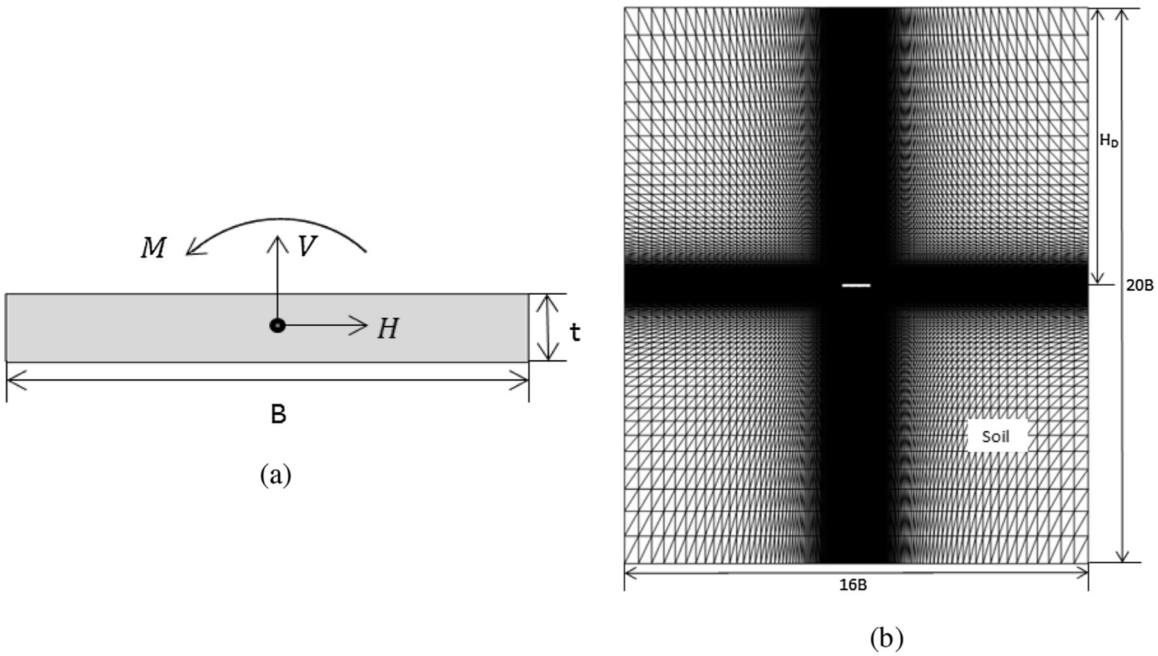

Fig. 1. Schematic of FE model: (a) Geometry of the anchor fluke; (b) meshes of FE model.

depth. The soil shear strength (S_u) at depth z is generally expressed as $S_u = S_{u0} + kz$, in which S_{u0} is the soil shear strength at the surface of the seabed and k is the strength gradient. Merifield et al. [2] studied the effect of soil non-homogeneity (linearly increasing shear strength) on the pullout capacity factor in weightless soil by upper bound and lower bound analyses. The dimensionless non-homogeneity factor kB/S_{u0} (where B is the anchor width) is introduced to consider the variation of linearly increasing soil shear strength profile. But the range of kB/S_{u0} investigated by Merifield et al. [2] does not cover all the possible cases in the field. Yu et al. [8] conducted small strain analysis to study the effect of soil strength profile for plate anchors considering the anchor inclination, breakaway condition and overburden pressure. A dimensionless factor kB/S_{uH} is defined differently from that of Merifield et al. [2], in which S_{uH} is the soil shear strength at the embedment depth of the anchor plate. Tho et al. [9] applied large deformation finite element method to investigate the influence of kB/S_{u0}. A wide range of kB/S_{u0} is applied in the study. However, Merifield et al. [2] does not consider the anchor plate thickness. Studies of Tho et al. [9] are on pullout capacity of square plate anchor with plate aspect ratio (width B over thickness t) of 20, which is typically used in studies on plate anchors. There is a lack of studies on vertical, horizontal and rotational capacity of drag anchor which has smaller aspect ratio B/t, which is 7 typically used in previous studies on drag anchor.

The plastic yield envelope was initially used to describe the response of offshore foundations under combined loading for the determination of foundation capacity. Bransby and O'Neill [10] proposed a method of using the yield envelope to predict drag anchor installation behavior. In the prediction analysis, the yield envelope of anchor fluke is used to determine the loads on the anchor fluke. The resistance of shank is calculated as the normal force and sliding force on the shank. The anchor line equation is used for the calculation of the anchor line force and anchor line angle. By ensuring the anchor force system, which includes the forces on the fluke, shank and anchor line, is in equilibrium at each advancing step, the anchor trajectory is predicted. The yield envelope for deep anchor failure mechanism was obtained using finite element study in Bransby and O'Neill [10]. After the studies of anchor capacity under unidirectional loading which provide the maximum loads without loading combination, a series of fixed ratio displacement studies are conducted in two-dimensional and multi-directional loading to get the loads at failure by finite element analysis. The yield envelope can be expressed as a function of failure loads V,H and M as $f(V, H, M) = 0$. With the maximum loads V_{max},H_{max} andM_{max}, the envelope can be expressed as a function of the failure loads V, H andM by the offset form from Murff [11]:

$$f = \left(\frac{V}{V_{max}}\right)^q + \left[\left(\frac{M}{M_{max}}\right)^m + \left(\frac{H}{H_{max}}\right)^n\right]^{\frac{1}{p}} - 1 \tag{1}$$

where f is the yield envelope function, V_{max},M_{max}, andH_{max} are the maximum loads/moment per unit length of anchor plate for plane strain condition, andm n,p,q are exponents determined by least square regression analysis.

O'Neill et al. [6] gave the yield envelope functions for anchor plates with uniform thickness and wedge shape with deep localized failure in the kinematic analysis of drag anchor. Elkhatib and Randolph [7], and Elkhatib [12] provided yield envelopes for the simplified uniform thickness anchor plate with aspect ratios of 20 and 7 for the prediction analysis of VLA. The influence of anchor plate/soil interface friction on the maximum capacity was studied. The yield envelope function for an interface friction coefficient of 0.4 and a rough interface were given. Studies on VLA using the yield envelope method were also conducted by Andersen et al. [13] and Yang et al. [14]. Cassidy et al. [15] applied the yield envelope method for the analysis of the keying process of SEPLA by using the yield envelope parameters especially for SEPLA with shank. Wei et al. [16] and Liu et al. [17] studied the yield envelope for deeply embedded OMNI-MAX anchor and used the yield envelope method for the analysis of the anchor keying process. For SEPLA and OMNI-MAX anchors with deep embedment depth where localized failure occurs, application of the yield envelope from deep anchor behavior for analysis of the whole keying process analysis is reasonable. However, for drag anchor installing from shallow depth to the final depth when localized failure happens or shallowly embedded OMNI-MAX anchor which is more practical in the field, ignoring the influence of shallow anchor behavior is not reasonable. Moreover, most of the previous studies of yield envelope are for soils with uniform shear strength profile.